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(54) Membrane Electrode Assembly

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IMPROVED MEMBRANE ELECTRODE ASSEMBLY

INTRODUCTION

This invention relates to a membrane electrode and seal assembly and, more particularly, to such an assembly used in solid polymer type fuel cells.

BACKGROUND OF THE INVENTION

Fuel cells using membrane electrode assemblies are known and have been produced and sold by the applicant. Such cells are known as solid polymer type fuel cells which comprise, in the heart of the system, two porous electrodes separated by an electrolytic material. The porous electrodes and the electrolytic material form an assembly called a "membrane electrode assembly" or "MEA". The MEA is located between two electrical conducting or graphite plates. The graphite or field flow plates supply fuel and oxidant in the form of hydrogen and air or oxygen, respectively, to the MEA and also act to provide current generated by the fuel cell to an external electrical circuit where it may be stored or otherwise used. The fuel and oxidant are supplied to the MEA by grooves in the surface of the plates adjacent the membrane which communicate with manifolds carrying gases to each of the individual cell assemblies.

The assembly further includes a catalytic material on the surface of each electrode which contacts the electrolytic membrane. The electrodes are each made from porous carbon fibre paper or "CFP" which has been rendered hydrophobic. Ridges between the grooves in the plates also contact the electrode. The MEA consumes the fuel and oxidant through an electrochemical process and

produces an electrical current which can be drawn from the electrodes to an external circuit.

It is important to ensure that the fuel and oxidant gases supplied to the MEA do not mix and, to that end, sealing the gases to prevent such mixing is imperative. In the event that hydrogen and oxygen combine within the fuel cell in combination with an appropriate catalyst which may also be present, a combustible mixture can form and inflame. In the event that the fuel and oxidant leak from the interior to the exterior of the fuel cell, it can reduce the efficiency of the fuel cell and can also create a fire or explosive hazard.

In one previous fuel cell, an MEA was used between the two electrical conducting or graphite plates which included an electrolytic membrane bonded between the two electrodes. This membrane extended substantially beyond the edge or periphery of the electrodes and was not supported by or bonded to them. The electrodes covered only the inner or active portion of the membrane and the outer periphery of the membrane was free of the electrodes.

This membrane electrode assembly was disadvantageous for several reasons. First, the membrane was installed between two adjacent electrical conducting plates and acted as a gasket sealing the gases in the electrode region from the exterior, isolating the gases in their respective manifolds and electrically insulating the electrical conducting flow field plates between which it was installed.

Such electrolytic membranes, however, did not function well as gaskets. The membranes were subject to shrinking and swelling depending on the water content of

the membrane. Since they were free to shrink and swell, the potential for tearing or for fatigue cracks to form was high. Although various techniques were utilized in an attempt to minimize the leaks across the membrane between the flow field plates, the techniques were expensive and leaks continued to result.

With the unsupported membrane of the previous membrane assembly, it was also necessary to machine a recess in each flow field plate contiguous with the periphery of the electrode so that the MEA could be appropriately positioned between the flow field plates with a uniform distance being maintained about the periphery so that the membrane could be tightened appropriately between the plates so as to function with a good sealing action. Such machining was time consuming and expensive and, in fact, assisted only slightly in enhancing the sealing action.

Yet a further disadvantage with the previous assembly was that the membrane itself was difficult to position and to be maintained in position while the stack assembly was being assembled. This was so since the membrane is quite thin and is inherently very flexible in addition to being subject to expanding and contracting due to the humidity changes in the gases to which the membrane was subjected.

It was also necessary in the prior membrane electrode assembly to position seals about the water and gas passages which extended through the flow field plates and the membrane. This was accomplished by machining grooves in the graphite field flow plates on either side of the membrane assembly and manually positioning rubber seals in the grooves. This was time consuming. Likewise, when assembling the cells, the seals could be dislodged

from the grooves if of an O-ring configuration or, if of a rectangular configuration, could be rolled in their grooves. In either case, the sealing action was adversely affected.

SUMMARY OF THE INVENTION

According to one aspect of the invention, there is provided a membrane electrode assembly for an electrochemical fuel cell comprising first and second layers of porous electrically conductive sheet material and a membrane interposed therebetween, said layers of sheet material covering and supporting substantially the entire surface of said membrane.

According to a further aspect of the invention, there is provided a method of forming a membrane assembly comprising the steps of bonding a solid polymer ion exchange membrane between two layers of porous electrically conductive sheet material, said layers of sheet material covering and supporting substantially the entire surface of said membrane, said layers of sheet material and said membrane having openings formed therein to accommodate the passage of fluids through said assembly, forming grooves in the surfaces of said layers of sheet material facing away from said membrane, said grooves generally circumscribing said fluid passage openings, and depositing an extrudable sealant material into said grooves.

According to yet a further aspect of the invention, there is provided a method of forming a membrane assembly comprising the steps of bonding a solid polymer ion exchange membrane between two layers of porous electrically conductive sheet material, said layers of sheet material covering and supporting substantially the entire surface of said membrane, said layers of sheet material covering and supporting substantially the

entire surface of said membrane, said layers of sheet material and said membrane having openings formed therein to accommodate the passage of fluids through said assembly, impregnating the surfaces of said layers of sheet material facing away from said membrane with a sealant material, said sealant material generally circumscribing said fluid passage openings.

According to yet a further aspect of the invention, there is provided a membrane assembly for the humidification section of an electrochemical fuel cell comprising first and second layers of a porous sheet material and a water permeable membrane interposed therebetween, said layers of sheet material covering and supporting substantially the entire surface of said membrane.

According to yet a further aspect of the invention, there is provided a method of forming a membrane assembly comprising the steps of bonding a water permeable membrane between two layers of porous sheet material, said layers of sheet material covering and supporting substantially the entire surface of said membrane, said layers of sheet material and said membrane having openings formed therein to accommodate the passage of fluids through said assembly, forming grooves in the surfaces of said layers of sheet material facing away from said membrane, said grooves generally circumscribing said fluid passage openings, and depositing an extrudable sealant material into said grooves.

According to yet a further aspect of the invention, there is provided a method of forming a membrane assembly comprising the steps of bonding a water permeable membrane between two layers of porous sheet material, said layers of sheet material covering and

supporting substantially the entire surface of said membrane, said layers of sheet material and said membrane having openings formed therein to accommodate the passage of fluids through said assembly, impregnating the surfaces of said layers of sheet material facing away from said membrane with a sealant material, said sealant material generally circumscribing said fluid passage openings.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

A specific embodiment of the invention will now be described, by way of example only, with the use of drawings in which:

Figure 1 is a diagrammatic side view of the stack assembly for a fuel cell incorporating the membrane electrode and seal assembly according to the invention;

Figure 2 is an end view of the fuel cell stack assembly illustrated in Figure 1;

Figures 3A and 3B are a front diagrammatic view of a typical fluid flow field plate and an enlarged cross-sectional view of the fluid flow groove in the field plate, respectively;

Figure 4 is a front view of a membrane electrode assembly according to the invention;

Figure 5 is a side view of the membrane electrode assembly of Figure 4;

Figure 6 is an exploded isometric view of the membrane electrode assembly of Figures 4 and 5;

Figure 7 is a diagrammatic schematic illustration of the flow through the fuel cell; and

Figure 8 is a cross-sectional enlarged view of a typical sealing groove in the electrode taken along VIII-VIII of Figure 4.

DESCRIPTION OF SPECIFIC EMBODIMENT

Referring now to the drawings and, in particular, to Figure 1, a fuel cell is generally illustrated at 16. It includes a stack assembly generally illustrated in exploded form at 10. It further includes a pair of end plates 11, 12 which could be fluid end plates which terminate the stack assembly 10 and a plurality of tie rods 15 extending between the end plates 11, 12 to retain and hold the stack assembly 10 in its assembled condition.

A spacer plate 13 and an electrical isolation plate 14 are positioned inside the end plate 11 and a piston 17 is positioned within the end plate 12. Buss plates 20, 21 are located on opposite ends of the stack assembly 10 as indicated and carry the voltage and current generated by the fuel cell 16. Cooling water jackets 22, 23 are located immediately inside the buss plates 20, 21.

The stack assembly 10 includes a so-called "active" section generally illustrated at 24 and a "humidification" section generally illustrated at 30. The active section 24 includes in addition to the buss plates 20, 21 and cooling water jackets 22, 23, a plurality of identical assemblies illustrated generally at 31, each assembly consisting of three fluid flow field or graphite plates 32, 33, 34 and two membrane electrode assemblies ("MEA's") generally illustrated at 40 which are assembled

between the plates 32, 33, 34. In each assembly 31, the leftmost flow plate 32 carries the fuel in the form of hydrogen gas, the centre flow plate 33 carries the oxidant in the form of oxygen or air on one side and hydrogen on the opposite side and the rightmost plate 34 carries the oxidant on the side adjacent the MEA 40 and water on the opposite side. The configuration of the assembly 31, therefore, provides for the hydrogen and the oxidant to be located on opposite sides of each membrane electrode assembly 40 and a coolant fluid flow plate in the form of a coolant jacket which is, in the present instance, a water jacket, to be located adjacent each hydrogen flow field plate. This configuration is typical and extends throughout the active section 24.

The humidification section 30 includes a plurality of oxidant flow field plates 41 generally located on the left hand side of the humidification section 30 illustrated in Figure 1 and a plurality of fuel humidification flow field plates 42 generally located on the right hand side of the humidification section 30, a plurality of fuel humidification membranes 37 and a plurality of oxidant humidification membranes 36 positioned between the fuel humidification flow field plates 42 and the oxidant flow field plates 41, respectively. The humidification section 30 acts to humidify the gases used so that the membranes 43 in the active section 24 will remain moist or wet as described hereafter. The membranes 43 will otherwise allow gases to diffuse therethrough in the event the membranes 43 are allowed to dry. This may create a potential safety hazard and reduce cell efficiency. The humidification section 30 is intended to prevent this eventuality.

The active section 24 also differs from the humidification section 30 in the fact that there is no

electricity produced in th humidification section 30 whereas in the active section 24 electricity, of course, is produced by reason that a catalyst in the form of platinum is present in the membrane electrode assemblies 40.

The membrane electrode assemblies 40 in the active section 24 are identical and a typical one is illustrated at 40 in Figures 4, 5 and 6. It comprises three elements, namely a first layer being an electrode made from porous carbon fibre paper ("CFP") 44, a second layer of an electrolytic material which is a solid, polymer, ion exchange membrane 43 and a third layer being a further electrode made from porous carbon fibre paper 50, the electrodes 44, 50 of carbon fibre paper sandwiching the membrane 43 therebetween to form an integral assembly 40 as described in greater detail hereafter.

The coolant fluid flow plate 22 is illustrated in Figures 3A and 3B. One side 102 of the plate 22 is blank but the opposite side 103 as illustrated has a plurality, namely ten(10), liquid carrying grooves 51 formed therein to carry the coolant, namely water vapour, from the inlet 100 to the outlet 101 although only one groove 51 is illustrated for ease of illustration. In addition, a plurality of holes (not shown) extend through the plate 22 to allow for passage of the hydrogen, the air or oxidant through the plate 22.

The plate 22, as described, is mounted against the blank side of the hydrogen flow field plate 32 (Figure 1). To that end, it is necessary to seal the plate 22 against the blank side of fuel plate 32 to prevent the escape of water. Reference is made to sealing groove 104 in Figure 3B which carries sealant material in the form of

silicon rubber r elastomer material 110. Groove 104 is machined in plate 22 and the sealant material 110 is injected into the groove 104 prior to assembling the stack assembly 10 and, in particular, prior to assembling the plate 22 against the fuel flow field plate 32.

Referring again to the membrane electrode assembly 40 of Figures 4, 5 and 6, the two electrodes 44, 50 sandwich the membrane 43 completely therebetween so as to form an integral unit. It will be particularly noted that the membrane 43 is sandwiched between the electrodes 44, 50 over its entire working area and that the holes 52, 111, 113 for the oxidant, water vapour and fuel, respectively, extend through not only the membrane 43 but also through the electrodes 44, 50 and are conterminous through the three members 44, 43, 50. The membrane 43 permits the diffusion through the membrane 43 of hydrogen ions and is intended to be substantially impervious to hydrogen and oxygen molecules. A catalyst 54, in the present case being platinum, is added to the side of the electrodes 44, 50 adjacent the membrane 43. The catalyst reacts with the hydrogen ions and thereby produces the electrical current generated at the buss plates 20, 21.

With reference now to Figure 8, sealing grooves 60, 61 are formed in the electrodes 44, 50, respectively, but do not, of course, extend through the membrane 43 although they extend up to each side of the membrane as illustrated in Figure 8. The sealing grooves 60, 61 are injected with sealant material 62 prior to assembling the fuel cell 16. An appropriate sealant material 62 is a silicon rubber material and a suitable material is known as SILASTIC E RTV material.

The membrane electrode assembly 40 is assembled by initially submerging the carbon fibre paper 44,50 into

a mixture of hydrochloric acid and TEFLON. The carbon fibre paper 44, 50 is allowed to absorb the hydrochloric acid and TEFLON overnight. The carbon fibre paper 50 is then removed from the mixture and placed on a hot plate at a temperature of approximately 500 - 600° to melt and bond the TEFLON mixture to the carbon fibre paper 44,50 in a "sintering" process. When the sintering process is complete, the carbon fibre paper 44, 50 is spread with a mixture of a platinum catalyst and TEFLON which is also bonded within the carbon fibre paper 44, 50 in a further sintering process.

Two electrodes 44, 50 are, of course, used with each membrane 43 for each membrane electrode assembly 40. The bonding of the electrodes 44, 50 with the membrane 43 is done under a combined process of heat, pressure and time until the bonding process is complete and the membrane electrode assembly 40 is formed into a single assembly. The process involves placing the assembly 40 in a press at a temperature of 175°C and increasing the pressure to 600 p.s.i. A coolant drops the temperature to approximately 80°C over 20 minutes and the bonding process is complete.

The assembly 40 is then milled so as to provide the sealing grooves 60, 61. Subsequently, the coolant, oxidant and fuel holes represented by holes 111, 52, 113 illustrated in Figure 4 and the guide pin holes 121, 122 which are used for assembly purposes are punched through the electrodes 44, 50 and the membrane 43. The sealant material 62 is injected into the sealing grooves 60, 61 on both sides of the electrode assembly 40.

The fuel cell 16 is then assembled by using the guide pin holes 121, 122 as guides for guide pins (not shown). The various components are stacked together and,

when assembled, the nuts 120 (Figure 1) on the ends of the fuel cell 16 are torqued to their proper value.

OPERATION

Reference is now made to Figure 7 which illustrates the operation of the fuel cell 16. The fuel in the form of hydrogen passes from the hydrogen supply 70 and enters the humidification section 30 through the fuel humidification flow field plates 42 (Figure 1) where it is humidified by the water carried by the humidified water jacket plates 39 to a value preferably close to 100% humidity. The humidified fuel gas then passes to the active section 24 of the stack assembly 10 where it passes through the hydrogen or fuel flow field plates 32 adjacent the anode side of the membrane electrode assemblies 40 wherein hydrogen ions diffuse through the membrane 43. The hydrogen exits the plate 32 in the active section 24 and passes to a tank 64 where excess hydrogen may be returned to the inlet line 63 and wherein the above-identified process is repeated.

The oxidant in the form of air or, preferably, oxygen enters the humidification section 30 of the stack assembly 10 where it is humidified as it passes through the oxidant flow field plates 41 (Figure 1) adjacent the humidification water jacket plates 39. It then passes to the active section 24 and through the oxidant or fuel flow field plates 33, 34 adjacent the cathode side of the membrane electrode assemblies 40. The air or oxygen then flows out of the active section 24 to a tank 71 where any pressure exceeding a certain value is vented and where any water formed may be returned to the fuel cell 16.

Water vapour is provided to the active section 24 of the fuel cell 16. The water vapour travels through

the water jacket flow field plates 22, 34 adjacent the hydrogen and oxygen flow field plates 32, 33. It then travels to the humidification section 30 and thence to tank 71 where it can be returned to the fuel cell 16 by a pump 72.

Many modifications will readily occur to those skilled in the art. For example, rather than a graphite material being used for the electrical conducting plates, other substances could be used including a composite material of KYNAR and graphite powder. Likewise, an elastomer material could be used for the coolant material rather than rubber. It will also be understood that the electrode material may not necessarily be hydrophobic matter although in the present case, it is so desirable. Although platinum is used as a catalyst in the present instance, it would of course, be possible to use other substances to increase the reaction rate. Many further modifications will readily occur to those skilled in the art to which the invention relates and the specific embodiments described herein should be taken as illustrative of the invention only and not as limiting its scope in accordance with the accompanying claims.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A membrane electrode assembly for an electrochemical fuel cell comprising first and second layers of porous electrically conductive sheet material and a membrane interposed therebetween, said layers of sheet material covering and supporting substantially the entire surface of said membrane.

2. The membrane electrode assembly of claim 1 wherein said membrane is a solid polymer ion exchange membrane.

3. The membrane electrode assembly of claim 2 wherein said sheet material comprises carbon fiber paper.

4. The membrane electrode assembly of claim 3 wherein said membrane has a thickness between about .001 inches and about .005 inches.

5. The membrane electrode assembly of claim 1 wherein each of said layers of sheet material further includes a catalyst on at least a portion thereof, said layers of sheet material rendered electrochemically active in the area containing said catalyst.

6. The membrane electrode assembly of claim 5 wherein said catalyst comprises platinum.

7. The membrane electrode assembly of claim 5 wherein said catalyst is included on at least a portion of the surface of each of said layers of sheet material facing said membrane.

8. The membrane electrode assembly of claim 7 wherein said catalyst is included on the central portion of each of said layers of sheet material, said central portion substantially coinciding with the flow field carrying reactant gas to said sheet material layer.

9. The membrane electrode assembly of claim 5 wherein said layers of sheet material and said membrane are bonded together to form a consolidated membrane electrode assembly.

10. The membrane electrode assembly of claim 5, said layers of sheet material and said membrane having openings formed therein to accommodate the passage of fluids through said assembly.

11. The membrane electrode assembly of claim 10 wherein said fluids include fuel gas, oxidant gas and coolant.

12. The membrane electrode assembly of claim 11 wherein said coolant is water.

13. The membrane electrode assembly of claim 11 wherein said coolant is ethylene glycol.

14. The membrane electrode assembly of claim 10 wherein each of said layers of sheet material has grooves formed in the surface thereof facing away from said membrane, said grooves having an extrudable sealant material deposited therein, said grooves generally circumscribing said fluid passage openings.

15. The membrane electrode assembly of claim 14 wherein said sealant material extends within the pores of said sheet material.

16. The membrane electrode assembly of claim 14 wherein said sealant material protrudes above said surfaces facing away from said membrane.

17. The membrane electrode assembly of claim 14 wherein said grooves extend substantially the entire thickness of each of said layers of sheet material.

18. The membrane electrode assembly of claim 17 wherein said sealant material contacts said membrane.

19. The membrane electrode assembly of claim 14 wherein said sealant material comprises silicon rubber.

20. The membrane electrode assembly of claim 10 wherein each of said layers of sheet material has grooves formed in the surface thereof facing away from said membrane, said grooves having an extrudable sealant material deposited therein, said grooves generally circumscribing the electrochemically active portion of said assembly.

21. The membrane electrode assembly of claim 20 wherein said sealant material extends within the pores of said sheet material.

22. The membrane electrode assembly of claim 20 wherein said sealant material protrudes above said surfaces facing away from said membrane.

23. The membrane electrode assembly of claim 20 wherein said grooves extend substantially the entire thickness of each of said layers of sheet material.

24. The membrane electrode assembly of claim 23 wherein said sealant material contacts said membrane.

25. The membrane electrode assembly of claim 20 wherein said sealant material comprises silicon rubber.

26. The membrane electrode assembly of claim 10 wherein the surfaces of said layers of sheet material facing away from said membrane are impregnated with a sealant material, said sealant material generally circumscribing said fluid passage openings.

27. The membrane electrode assembly of claim 26 wherein said sealant material protrudes above said surfaces facing away from said membrane.

28. The membrane electrode assembly of claim 26 wherein said sealant material extends substantially the entire thickness of said layers of sheet material.

29. The membrane electrode assembly of claim 28 wherein said sealant material contacts said membrane.

30. The membrane electrode assembly of claim 26 wherein said sealant material comprises silicon rubber.

31. The membrane electrode assembly of claim 10 wherein the surfaces of said layers of sheet material facing away from said membrane are impregnated with a sealant material, said sealant material generally circumscribing the electrochemically active portion of said assembly.

32. The membrane electrode assembly of claim 31 wherein said sealant material protrudes above said surfaces facing away from said membrane.

33. The membrane electrode assembly of claim 31 wherein said sealant material extends substantially the entire thickness of said layers of sheet material.

34. The membrane electrode assembly of claim 33 wherein said sealant material contacts said membrane.

35. The membrane electrode assembly of claim 31 wherein said sealant material comprises silicon rubber.

36. A method of forming a membrane assembly comprising the steps of:

bonding a solid polymer ion exchange membrane between two layers of porous electrically conductive sheet material, said layers of sheet material covering and supporting substantially the entire surface of said membrane, said layers of sheet material and said membrane having openings formed therein to accommodate the passage of fluids through said assembly,

forming grooves in the surfaces of said layers of sheet material facing away from said membrane, said grooves generally circumscribing said fluid passage openings, and

depositing an extrudable sealant material into said gr oves.

37. The method of claim 36 further comprising applying a mixture comprising a catalyst and polytetrafluoroethylene to the surface of each of said layers of sheet material facing said membrane.

38. The method of claim 37 wherein said catalyst is applied to at least a portion of the surface of each of said layers of sheet material facing said membrane.

39. The method of claim 38 wherein said catalyst comprises platinum.

40. A method of forming a membrane assembly comprising the steps of:

bonding a solid polymer ion exchange membrane between two layers of porous electrically conductive sheet material, said layers of sheet material covering and supporting substantially the entire surface of said membrane, said layers of sheet material and said membrane having openings formed therein to accommodate the passage of fluids through said assembly,

impregnating the surfaces of said layers of sheet material facing away from said membrane with a sealant material, said sealant material generally circumscribing said fluid passage openings.

41. A membrane assembly for the humidification section of an electrochemical fuel cell comprising first and second layers of a porous sheet material and a water permeable membrane interposed therebetween, said layers of sheet material covering and supporting substantially the entire surface of said membrane.

42. The membrane assembly of claim 41 wherein said membrane is a solid polymer ion exchange membrane.

43. The membrane assembly of claim 42 wherein said sheet material comprises carbon fiber paper.

44. The membrane assembly of claim 41, said layers of sheet material and said membrane having openings formed therein for accommodating the passage of fluids through the assembly.

45. The membrane assembly of claim 44 wherein said fluids include fuel gas and oxidant gas.

46. The membrane assembly of claim 44 wherein each of said layers of sheet material has grooves formed in the surface thereof facing away from said membrane, said grooves having an extrudable sealant material deposited therein, said grooves generally circumscribing said fluid passage openings.

47. The membrane assembly of claim 46 wherein said sealant material protrudes above said surfaces facing away from said membrane.

48. The membrane assembly of claim 46 wherein said grooves extend substantially the entire thickness of said layers of sheet material.

49. The membrane assembly of claim 48 wherein said sealant material contacts said membrane.

50. The membrane assembly of claim 46 wherein said sealant material comprises silicon rubber.

51. The membrane assembly of claim 44 wherein the surfaces of said layers of sheet material facing away from said membrane are impregnated with a sealant material, said sealant material generally circumscribing said fluid passage openings.

52. The membrane assembly of claim 51 wherein said sealant material protrudes above said surfaces facing away from said membrane.

53. The membrane assembly of claim 51 wherein said sealant material extends substantially the entire thickness of said layers of sheet material.

54. The membrane electrode assembly of claim 53 wherein said sealant material contacts said membrane.

55. The membrane assembly of claim 51 wherein said sealant material comprises silicon rubber.

56. A method of forming a membrane assembly comprising the steps of:

bonding a water permeable membrane between two layers of porous sheet material, said layers of sheet material covering and supporting substantially the entire surface of said membrane, said layers of sheet material and said membrane having openings formed therein to accommodate the passage of fluids through said assembly,

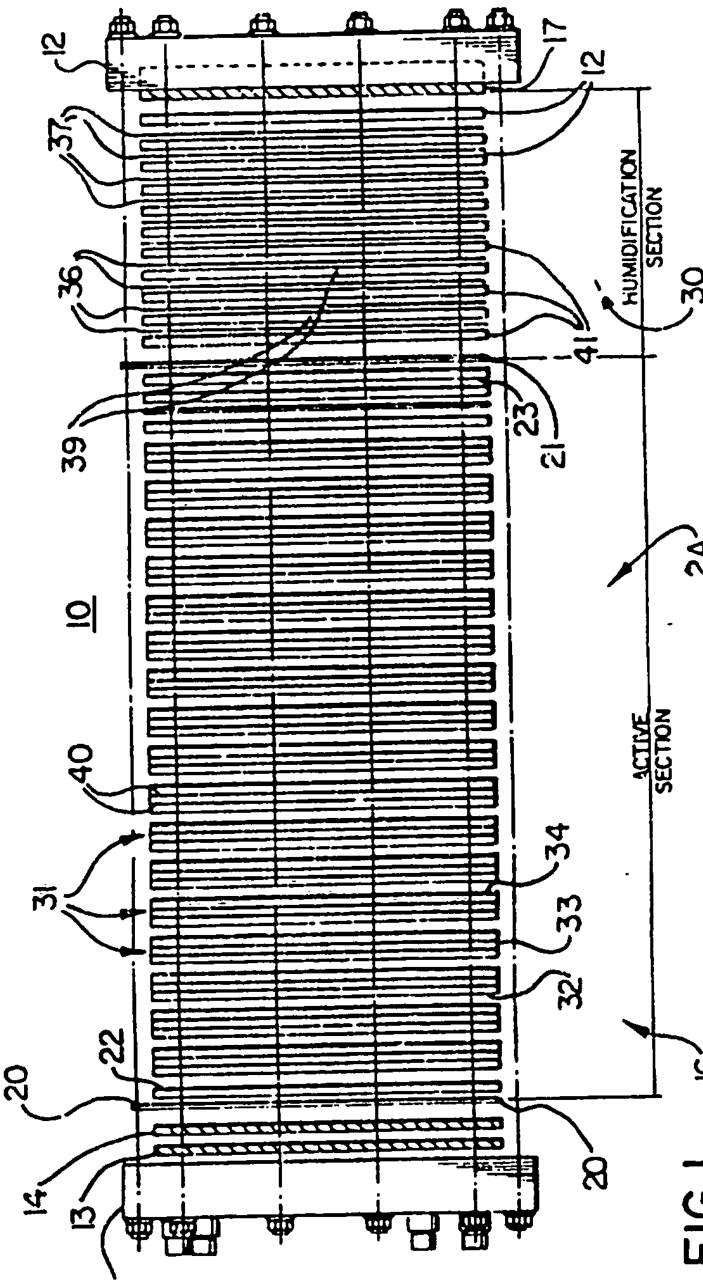
forming grooves in the surfaces of said layers of sheet material facing away from said membrane, said grooves g nerally circumscribing said fluid passage openings, and

depositing an extrudable sealant material into said grooves.

57. A method of forming a membrane assembly comprising the steps of:

bonding a water permeable membrane between two layers of porous sheet material, said layers of sheet material covering and supporting substantially the entire surface of said membrane, said layers of sheet material and said membrane having openings formed therein to accommodate the passage of fluids through said assembly,

impregnating the surfaces of said layers of sheet material facing away from said membrane with a sealant material, said sealant material generally circumscribing said fluid passage openings.


HUMIDIFICATION SECTION
ACTIVE SECTION
10
12
17
37
36
41
30
39
23
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2A
40
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11

FIG. 1

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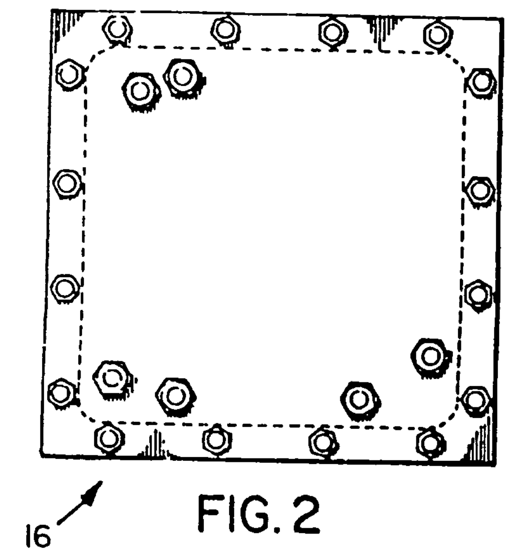

FIG. 2

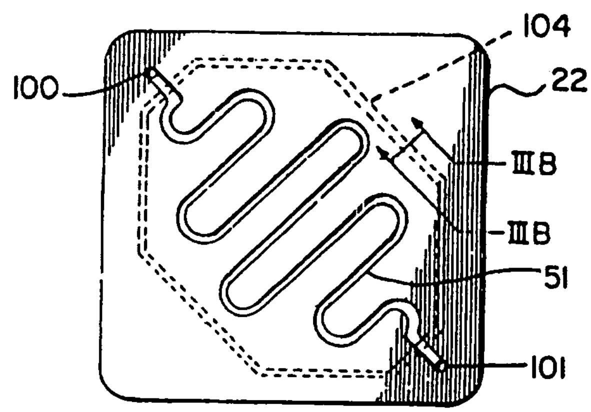

FIG. 3A

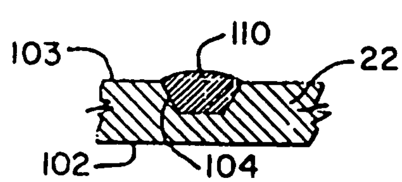

FIG. 3B

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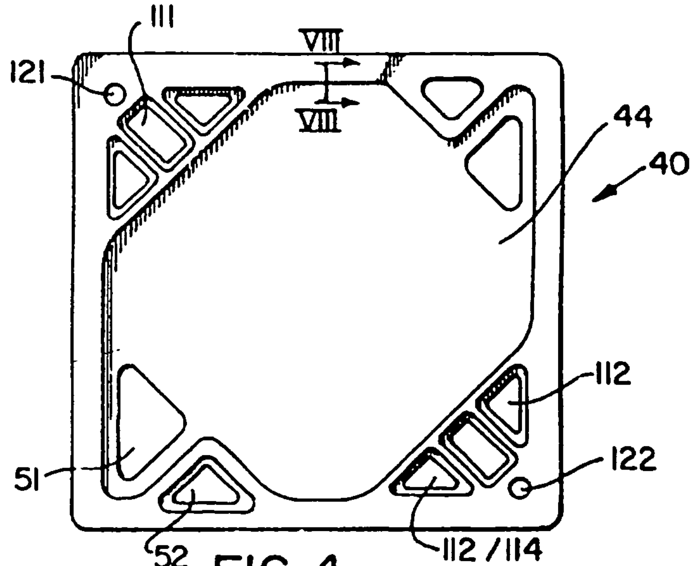

FIG. 4

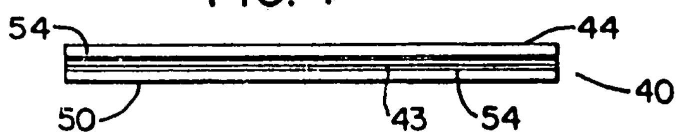

FIG. 5

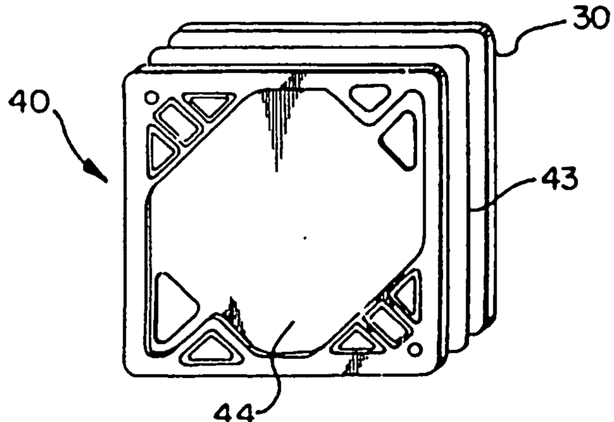

FIG. 6

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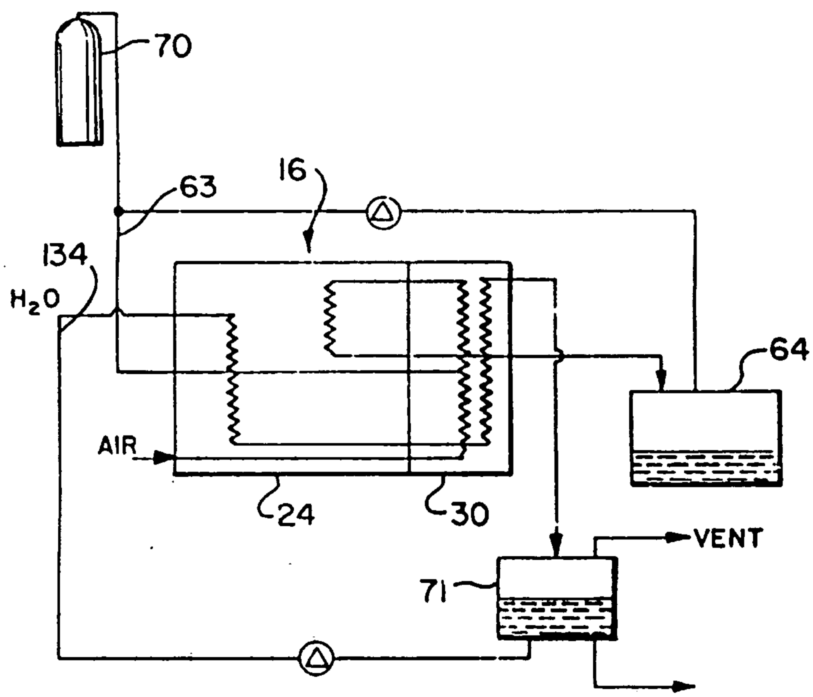

FIG. 7

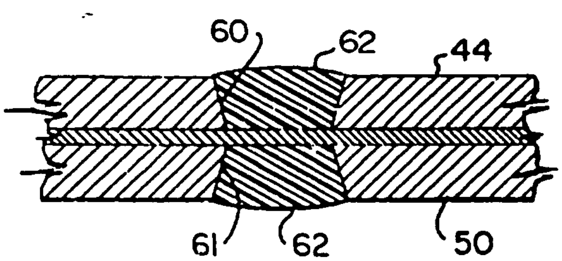

FIG. 8